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ARREST OF BRITTLE FRACTURES IN WIDE STEEL PLATES

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Program undertaken to investigate behavior of welded crack-arrester details which might be used under service conditions

BY R. J. MOSBORG, W. J. HALL AND W. H. MUNSE

SUMMARY. This paper describes an investigation which is concerned with an evaluation of various devices designed to arrest the propagation of brittle cracks. In the tests, brittle fractures are initiated by driving a wedge into a notch at the edge of steel plate specimens. The fracture propagates across the specimen until it encounters the arresting device. In order to evaluate the arresters, the tests are conducted at various combinations of temperature and stress.

Most of the work conducted to date has been concerned with the behavior of welded crack arresters composed of a strake of tough material butt welded so as to form an integral part of the structure. These tests indicate that, under certain conditions, strakes of tough material will arrest a propagating brittle crack. General observations from tests of welded arrester specimens, as well as from a few riveted arrester specimens, are presented.

Introduction

Object and Scope

During World War II, when brittle fracture became a serious problem in welded merchant ships, there was an immediate need for a means of reducing the probability of major ship structural failures. As a result, a method of arresting cracks was devised for structures already built. This consisted of slotting the main plate of the structure and riveting a doubler plate over the slot. Although this device usually worked satisfactorily, it was difficult to seal against leakage and, when used in tankers, was particularly hard to clean. In general, riveted arresters have been incorporated in ship construction since the war; a currently used detail consists of a riveted lap joint. It is likely that a limited number of riveted arresters will continue to be used in welded ship construction until dependable information becomes available on other types of large-scale arresters.

Laboratory studies have shown that for a given specimen geometry, once a brittle crack has been initiated and is propagating, it may be arrested by sufficiently reducing the average stress on the specimen or by adequately increasing the temperature of the material. However, from the practical point of view, control over the stress and temperature may be neither structurally feasible nor economical, particularly in large-scale structures which may be subjected to wide ranges of stress and temperature during service.

At present two other approaches to the problem of controlling brittle fractures in large-scale structures can be considered. These consist of (1) the use of a tough material throughout the entire structure to prevent the opportunity for brittle-fracture initiation and propagation or (2) the use of tough material butt welded in the structure at selected locations to stop cracks that might be propagating. Economic considerations may often dictate the approach to be used.

The program described in this paper was undertaken to investigate the behavior of welded crack arrester details that might be used under service conditions. In particular, the possibility of incorporating a strake of tough material or perhaps a tough weld as an integral part of the structure was studied. In the early stages of the program small-scale laboratory specimens were employed to determine whether this type of welded crack arrester would be feasible. After this preliminary work the primary emphasis was placed on the study of 6-ft wide specimens. This specimen was adopted because it was a convenient size and because it was felt specimens of this size might help in obtaining information which could more easily be related to full-scale conditions. A few riveted crack arrester specimens, fabricated according to a detail for which there was a large amount of service information, were tested to provide a basis for comparison. However, most of the program has been concerned with an investigation of welded arresters.

While this program is most directly related to ships, the principles studied in these tests could be useful in other structures (pipe lines, storage tanks, pressure vessels, etc.) where brittle fractures have occurred.

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Table 1—Chemical Composition and Mechanical Properties of Steels

(*a*) Chemical composition

Steel	Chemical Composition, % C	Mn	P	S	Si	Cu	Cr	Ni	Al	Mo	Va
E	0.21	0.34	0.019	0.030	0.01	0.18	0.12	0.19	0.003	..	..
T	0.11	0.84	0.036	0.015	0.28	0.32	0.50	0.99	0.09	0.53	0.095
X	0.20	0.76	0.019	0.040	0.03	0.04	0.02	0.16	0.002	..	..
Z	0.18	0.42	0.013	0.031	0.02	0.23	0.07	0.14	0.003	..	..

(*b*) Mechanical properties*

Steel	Yield strength, psi	Ultimate strength, psi	Elongation in 2 in., %	Reduction of area, %
E	32,100	64,900	35.8	56.7
T	111,900†	126,600	22.0	69.1
X	34,900	66,700	39.0	64.8
Z	34,700	68,100	36.5	57.6

* From Standard 0.505-in. diam specimens taken parallel to direction of rolling.
† Based on 0.2% offset.

Materials and Specimens

In order to evaluate various arrester devices, a starter material which would initiate and propagate a brittle crack under laboratory conditions was required. Two heats of rimmed steel (designated as steels E and Z) with Charpy V-notch 20 ft-lb values at about +70° F were available and were used to fabricate the riveted-arrester specimens and the portion of the welded-arrester specimens in which the crack was initiated. For the arresting material in the welded specimens, a steel possessing high strength and ductility (large energy absorbing capacity) was required. One of the steels readily available for this purpose at the beginning of the program was a low-alloy steel known as "T-1" (designated herein as Steel T). The mechanical properties and chemical composition for each of these steels are given in Table 1.

Two sizes of specimen, composed of inserts welded to long pull plates, were considered. The 2-ft wide specimens consisted of $^3/_4$- x 18- x 24-in. inserts butt welded to $^3/_4$-in. thick pull plates to provide a total specimen length of 6 ft. The 6-ft wide specimens usually consisted of $^3/_4$- x 54- x 72-in. inserts butt welded to 1-in. thick pull plates to provide a total specimen length of approximately 18 ft. All material was oriented with its direction of rolling parallel to the specimen axis and transverse to the direction of crack propagation.

The riveted arrester specimens contained a doubler plate which was riveted to one side of the main insert plate. The doubler plate was approximately the same length as the insert plate in the 2-ft wide specimens. However, it was 99 in. long in the 6-ft wide specimens so that it could be bolted to each pull plate to develop more fully the desired load in the doubler. These specimens are shown in Fig. 1. The

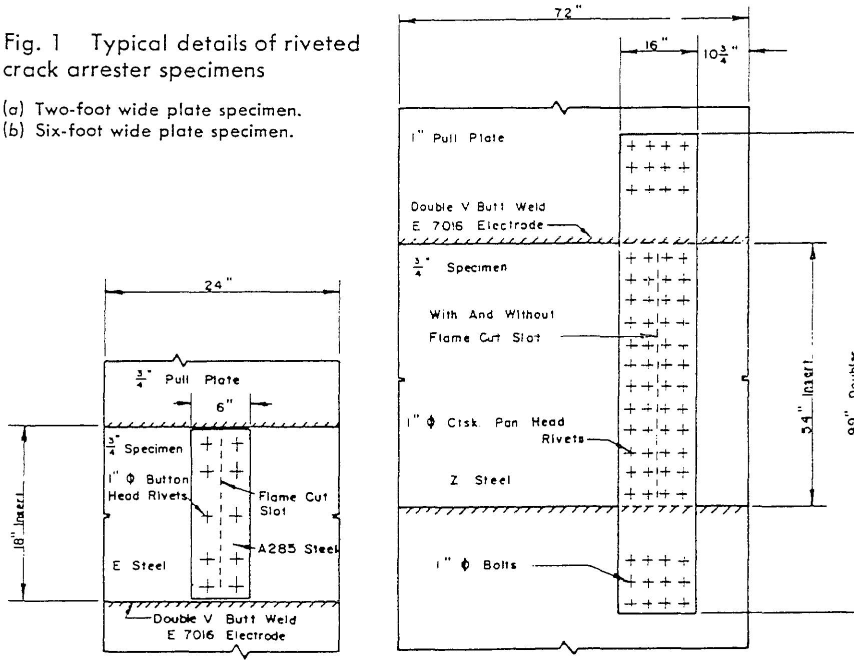


Fig. 1 Typical details of riveted crack arrester specimens

(*a*) Two-foot wide plate specimen.
(*b*) Six-foot wide plate specimen.

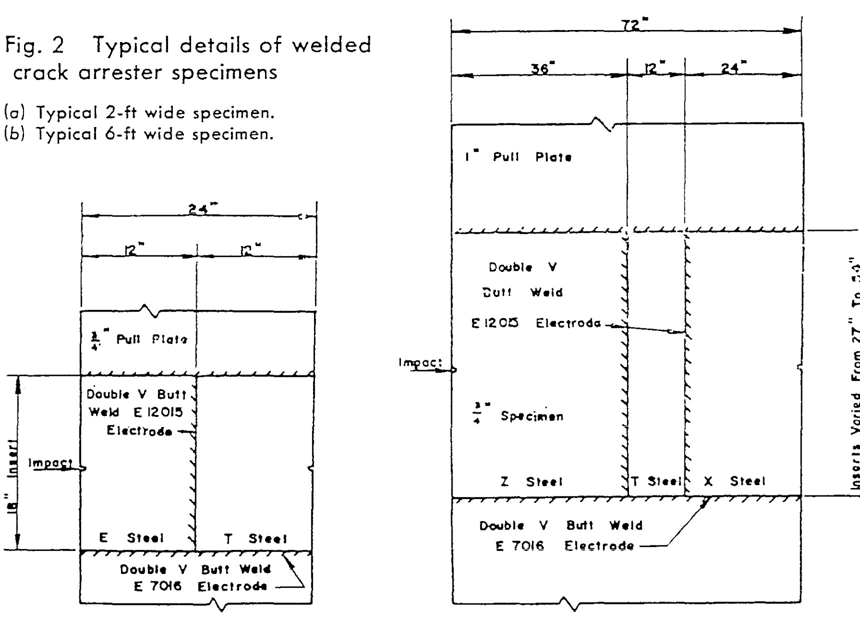


Fig. 2 Typical details of welded crack arrester specimens

(*a*) Typical 2-ft wide specimen.
(*b*) Typical 6-ft wide specimen.

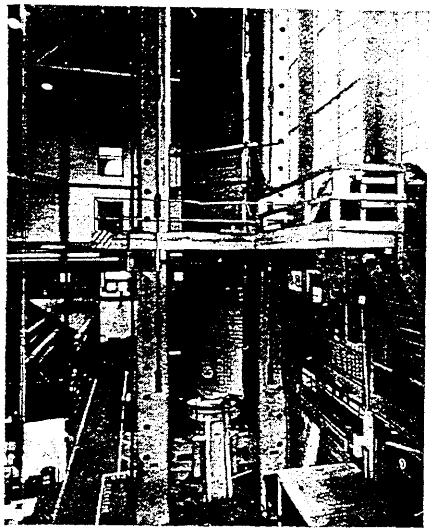


Fig. 3 Six-foot wide specimen ready for test in 3,000,000-lb machine

arrester detail in the large riveted specimens was the same as a design used for ships in service. The large riveted arresters were fabricated by a qualified shipbuilder to insure that the laboratory specimens were typical of actual practice. For comparative purposes in the test program, a few specimens were fabricated without a slot beneath the doubler.

The first type of 2-ft wide welded arrester specimen investigated was similar in makeup to the riveted doubler-type arrester and consisted of a slotted rimmed-steel insert plate with a single doubler plate of A-285 steel welded over the slot. Subsequently, both sizes of welded arrester specimens were composed of various widths of rimmed (steel E or Z), T, and in some cases a semikilled steel (designated as Steel X) which were butt-welded together in a single plane with E12015 electrodes to provide the total desired width of specimen. The brittle crack was generally started in the strake of rimmed steel and, by changing the position of this strake, the length of the crack introduced to the arrester system could be controlled. The width of T steel was varied so that the arresting effect of various widths of this tough material could be compared and semikilled steel was used where needed to fill out the total specimen width. After a test, the fractured portion of the specimen was removed or repaired to provide another test from the same insert whenever possible. Typical 2-ft and 6-ft wide welded specimens are shown in Fig. 2.

Description of Tests

The details of the testing procedure and instrumentation have been described previously[1] but are briefly summarized for convenience. To study the feasibility of arresting brittle fractures, a dependable method of initiating and propagating a brittle crack was required. The early development work on this program and on a closely allied program which is concerned with the mechanics of the propagation of brittle fractures resulted in the adoption of a notch-wedge-impact method similar to the SOD method[2] for crack initiation. In the method adopted, a gas-operated piston device is used to drive a cold chisel into a $1^1/_8$-in deep saw-cut notch (4-blade wide hacksaw cut terminated with a jeweler's saw-cut) at the edge of the specimen. A nominal impact of 1200 ft-lb is used for the initiation of the brittle cracks in all of the tests described The 2-ft wide specimens are tested in a 600,000-lb screw-type testing machine and the 6-ft wide specimens in a 3,000,000-lb hydraulic testing machine.

The specimens tested in the initial stages of this program had little or no instrumentation. As the program progressed, it became evident that instrumentation of the specimens to measure crack speed and strain history at selected locations would be desirable and perhaps essential for the eventual interpretation of the results. Also, data of this nature would permit correlation with the results from the related program on brittle fracture propagation. Crack speed on the surface of the specimen is obtained from a series of suitably spaced SR-4 Type A-9 strain gages (6-in. gage length, single wire) which, when broken by the propagating crack, interrupt an electrical circuit. From the distance between detectors and the time interval between interruptions of the circuit, the average crack speed is computed. The strain history at various locations is obtained from the response of SR-4 Type A-7 strain gages ($^1/_4$-in. gage length). The signals from the strain

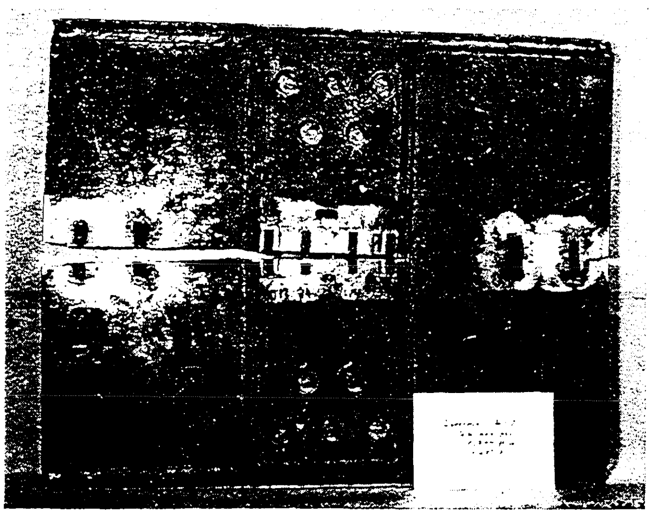


Fig. 4 Fracture path in 2-ft wide arrester specimen with fillet-welded doubler plate

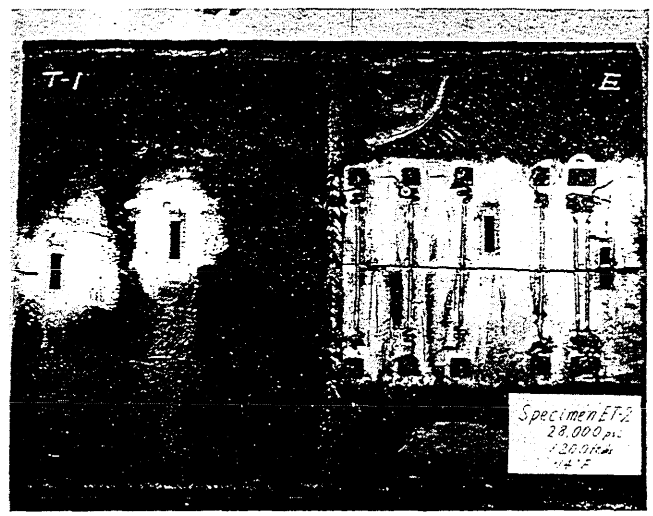
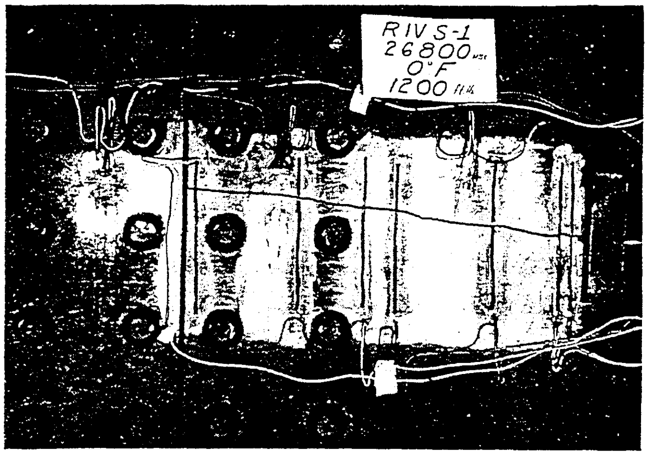


Fig. 5 Fracture path in 2-ft wide arrester specimen with butt-welded strake of *T* steel

Fig. 6 Fracture surface across 2-ft wide arrester specimen with tough butt weld joining two plates of rimmed steel



a

b

Fig. 7 Tests of 6-ft wide riveted arrester specimen with oxygen-cut slot

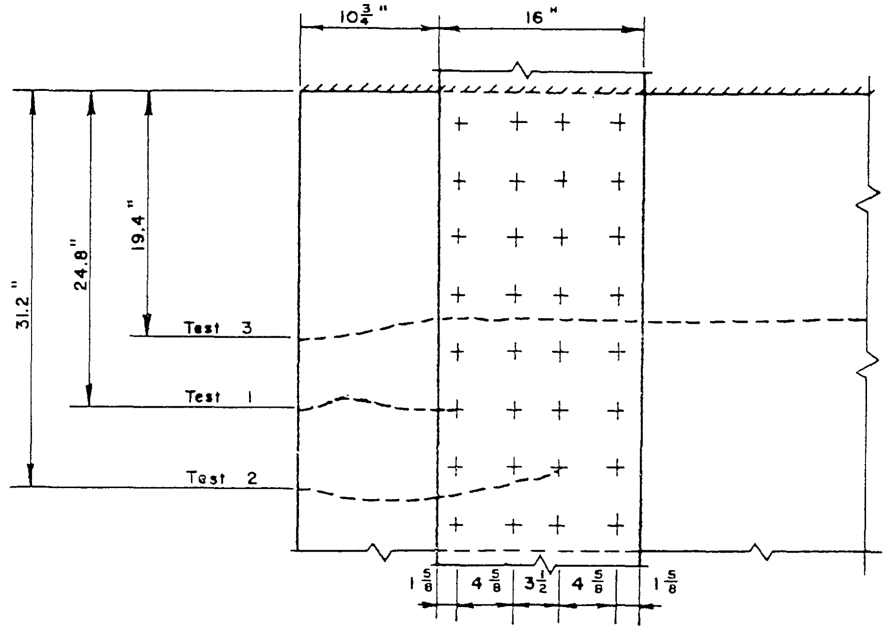
(a) Fracture path with crack initiated at edge near doubler.
(b) Fracture path with crack initiated at edge far from doubler.

gages and detectors are fed into cathode-ray oscilloscope equipment and recorded photographically with 35-mm strip-film cameras. For time intervals of 10 msec or less the strip-film camera is used as a single-frame camera to record the strain gage response as the trace moves once across the oscilloscope face at a predetermined sweep time. For times of several hundred milliseconds, the gage response is recorded on moving film. A detailed description of the sensing devices, recording devices, input circuits, triggering method, calibration procedure, stability, and data reduction process is presented in a previous paper.[1]

The specimen is cooled with crushed dry ice which is placed in containers hung on each side of the plate. In this manner, the specimens can be cooled to a temperature of approximately −20° F in about one and one-half hours.

Prior to the test the strain distribution in the specimen is checked at room temperature by applying the test load to the specimen at least once. After all instrumentation is checked, the specimen is cooled; the test load is applied; and the fracture is initiated by the notch-wedge-impact method. A 6-ft wide specimen ready for test is shown in Fig. 3.

In early tests on two foot wide specimens it was found that brittle fractures initiated by the notch-wedge-impact method consistently propagated completely across plain plate specimens of rimmed Steel E at an average stress of 15,000 psi, a temperature of 0° F, and a lateral impact of 1200 ft-lb. In general, the crack-arrester specimens are tested at higher stresses, somewhat lower temperatures, and the same lateral impact; this provides ample assurance of initiation and propagation of the brittle cracks in the starter material



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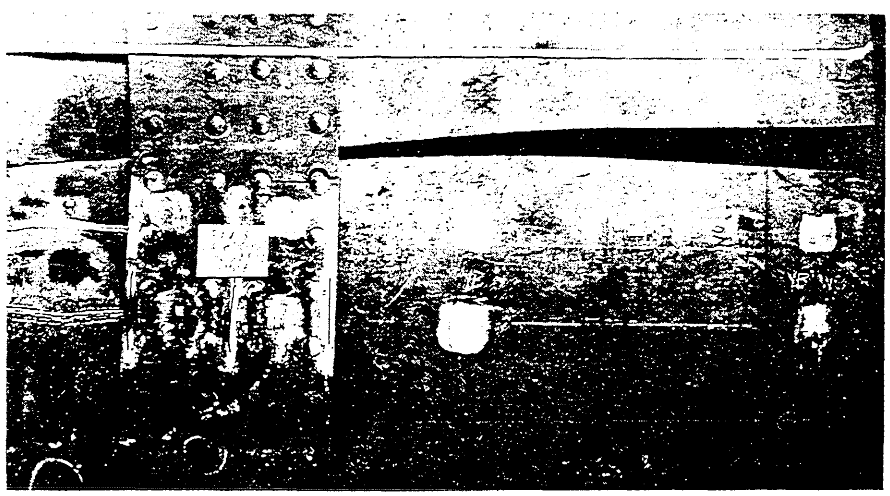


b

Fig. 8 Fracture paths in tests of 6-ft wide riveted crack arrester specimen without oxygen-cut slot

(a) Notch location and fracture path for three successive tests of same insert.
(b) Path resulting from third test of specimen.

and subjects the arresting device to stress and temperature conditions which are relatively severe when compared to service conditions.

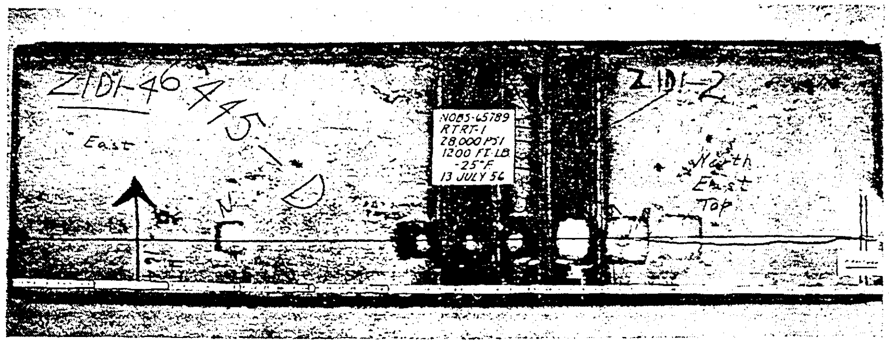
Test Results for 2-Ft Wide Specimens

The first type of welded crack-arrester specimen to be tested consisted of a doubler plate of A-2S5 steel plug and fillet welded over the slot in the main insert plate of rimmed Steel E. This arrangement was similar to a riveted doubler-plate detail used under service conditions.

Before welding the doubler plate to the main insert plate of one of these doubler-type specimens, SR-4 Type A-1 strain gages were mounted in a longitudinal direction $1^1/_2$ in. from each edge of the specimen ($^1/_2$ in. beyond the end of each notch). After the doubler had been welded to the insert plate, these gages near the edges of the plate indicated compressive residual strains as high as 1100 microinches per inch (μ in./in.). Thus, the fabrication of these specimens created approximately yield point compression at the base of the notch and a compressive strain field over the region ahead of the notch.

Whereas an applied tensile stress of about 15,000 psi was sufficient for the complete fracture of plain plate specimens of Steel E, an applied stress of over 22,000 psi was required for the initiation and propagation of brittle fractures in tests of the welded doubler-type specimens. Apparently, until offset by the application of a sufficiently large tensile stress, the aforementioned residual strain pattern hindered the initiation and propagation of a brittle crack in the specimens. A typical fracture of one of these doubler-type specimens is shown in Fig. 4. The brittle fracture propagated across the main plate to the oxygen-cut slot; also, it propagated through the connecting fillet weld and almost entirely across the attached doubler plate.

Because a slotted main plate and doubler plate combination would not be desirable in ships, particularly in tankers, only a few specimens of this type were tested. The program was then directed toward a study of specimens where the rimmed and tough steel were butt welded together in the same plane. The crack-arresting behavior of such a combination was studied in a preliminary fashion by butt welding 12-in. wide strakes of rimmed (E) and tough (T) steel together. SR-4 Type A-1 strain gages were mounted longitudinally $1^1/_2$ in. from the specimen edges before the two plates were butt welded together. After the fabrication of the specimen had been completed, compressive residual strains of less than 200 μ in./in. were present at these



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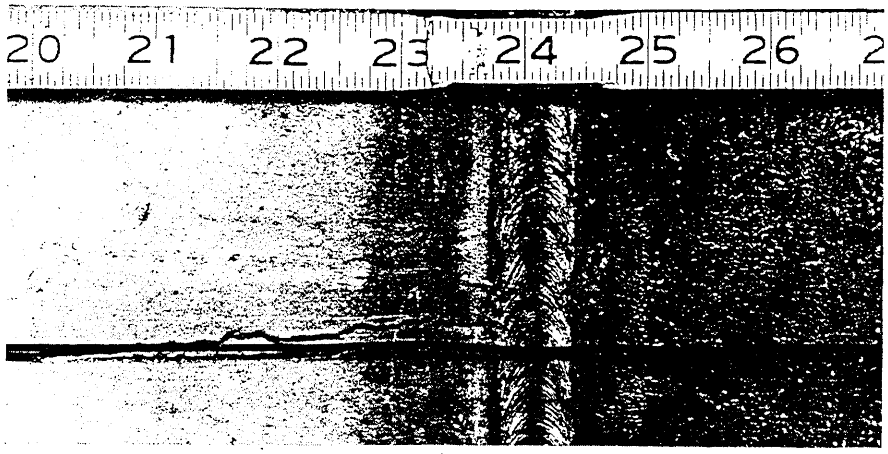
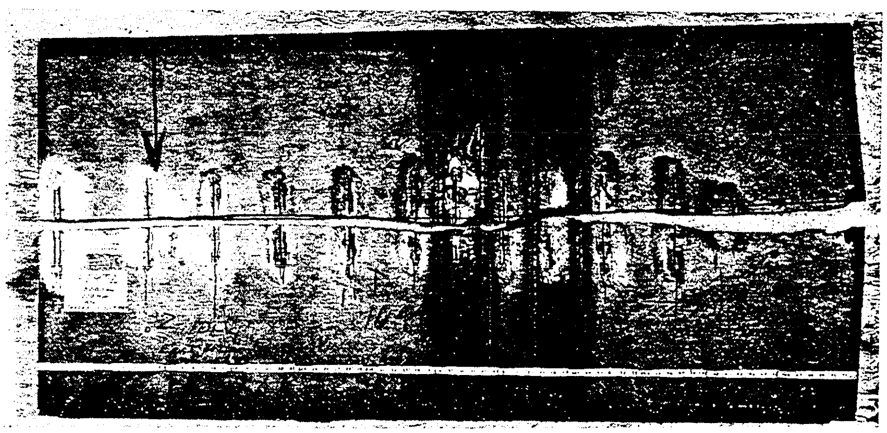


b

Fig. 9 Arrest of 2-ft long crack by 4-in. wide strake of *T* steel

(*a*) View of partially fractured insert.
(*b*) Surface of specimen around end of arrested crack.



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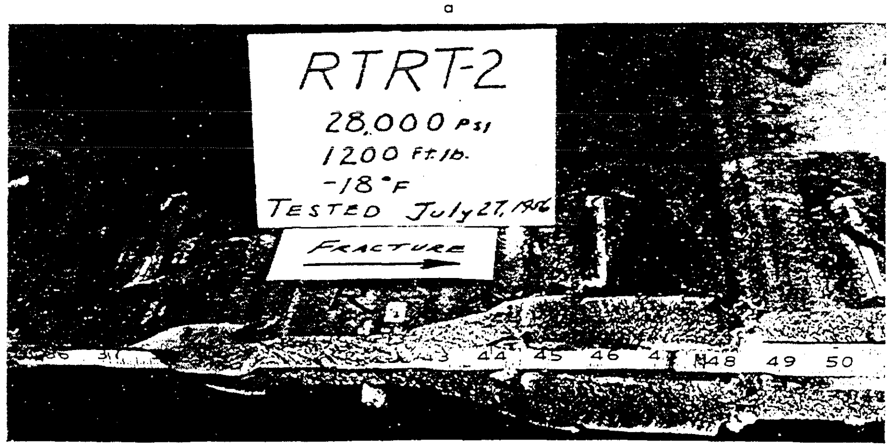

b

Fig. 10 Propagation of 3-ft long crack across specimen containing two 4-in. wide strakes of *T* steel

(*a*) Fracture path across specimen.
(*b*) Fractured surfaces of *T* steel strakes and adjacent rimmed steel.

locations as compared with residual strains of about 1100 μ in./in. for the doubler-type specimens at the same locations. At an average stress of 17,000 psi and a temperature of +16° F, a brittle crack was propagated across the 12-in. width of rimmed steel but was not evident on the surface of the specimen across or beyond the butt weld. Increasing the nominal test stress to 28,000 psi in another test resulted, as shown in Fig. 5, in a slight reduction of thickness through the butt weld indicating the presence of a submerged crack (a crack which has propagated a short distance within the plate but has not emerged to the surface).

One specimen, composed of two 12-in. widths of rimmed steel E butt welded together with E12015 electrodes, was tested at 25,000 psi and +30° F. With the exception of part of the butt weld, this specimen fractured completely in a brittle manner as shown in Fig. 6. Thus the tough weld alone was not sufficient to arrest the propagating crack. Measurements of average crack speed showed a value of approximately 3000 fps as the fracture approached the butt weld and less than 700 fps as the crack crossed the weld. No crack speed information was obtained in the material beyond the butt weld.

Test Results for 6-Ft Wide Specimens

A few tests were conducted on riveted crack-arrester specimens with two different geometries, with and without a longitudinal slot in the main plate beneath the doubler. However, the major emphasis was on welded arrester specimens containing various combinations of starter and arrester materials. For uniformity and comparative purposes similar values of average net-section stress and test temperature were adopted for these tests. It was felt that the nominal stress should be high, but not high enough to produce gross plastic strain in the specimen and the testing temperature should be low, but not excessively lower than service temperatures. On the foregoing basis, tests were generally conducted at an average stress of approximately 27,000 psi and a temperature of about −20° F.

One of the variables in the tests of this program was the length of brittle crack developed (width of starter material) before an arresting device was encountered. In the riveted arrester specimens, the crack propagated either approximately one foot or approximately four feet before encountering the region of the plate containing the doubler plate. In the various welded arrester specimens, the brittle crack propagated 1, 2, 3 or 4 ft before meeting a strake of tough material.

Crack detectors were placed on several of the riveted and welded arrester specimens in order that the speed of crack propagation in these specimens could be measured and compared with the speeds obtained in the tests of plain plate rimmed steel specimens. In general, the crack speeds in the starter strips of the arrester specimens were similar to the speeds obtained in the plain plate tests (primarily in the range of 3000 to 4000 fps) and were attained within the first 12 in. of travel from the notch. There appeared to be no increase of crack speed as the fracture progressed across the plate.

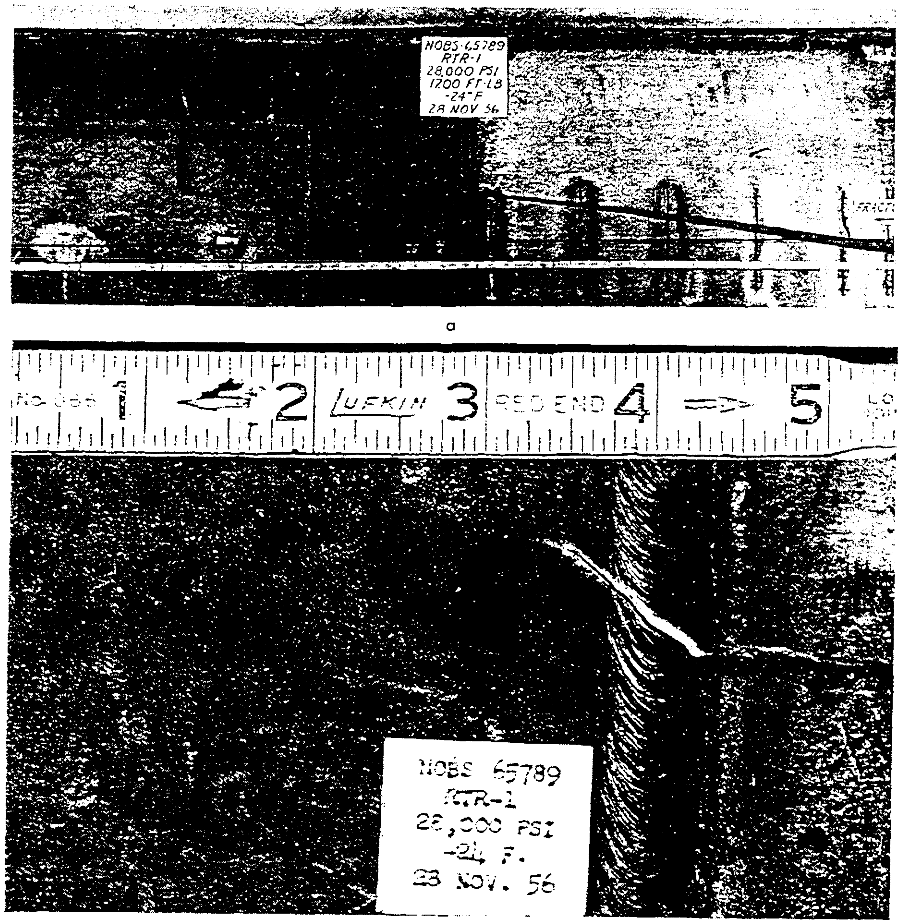

Fig. 11 Arrest of 3-ft long crack by 12-in. wide strake of *T* steel

(*a*) View of insert showing extent of propagation.
(*b*) Penetration of arrested crack into *T* steel.

Riveted Arrester Specimens

In the riveted specimens, the arresting device consisted of a 16-in. wide by 3/4-in. thick doubler plate riveted to one side of the main insert plate with four vertical lines of countersunk pan head rivets. In one case, the insert plate contained a longitudinal slot centered beneath the doubler plate and in the other case it did not. While only the slotted specimen is typical of a type of arrester in general use, it was felt that similar tests of an unslotted specimen would provide an opportunity to compare the effectiveness of the two details.

Two tests were made on a riveted doubler specimen in which an oxygen-cut slot had been placed in the insert plate beneath the doubler. In one case the brittle crack was initiated from a notch at the edge of the specimen near the doubler and in the other case from a notch at the edge of the specimen farthest from the doubler. The notches were in line with a horizontal row of rivets. In the first case, the crack traveled slightly upward so as to pass between the horizontal rivet rows and extend to the oxygen-cut slot in the main plate, Fig. 7 (*a*). No fracture was apparent in the doubler plate.

The partial fracture of the specimen in the test just described was rewelded. In the second test on the specimen the crack, initiated from a notch at the opposite edge of the specimen, propagated across the main plate to the oxygen-cut slot. In addition, the doubler plate fractured across two lines of rivets as shown in Fig. 7 (*b*). From this test, it seems that an abrupt discontinuity such as is provided by an oxygen-cut slot is a satisfactory form of crack-arresting device, provided the redistribution of stress is not too great. In addition, it appears that a rivet hole also possesses some degree of arrest

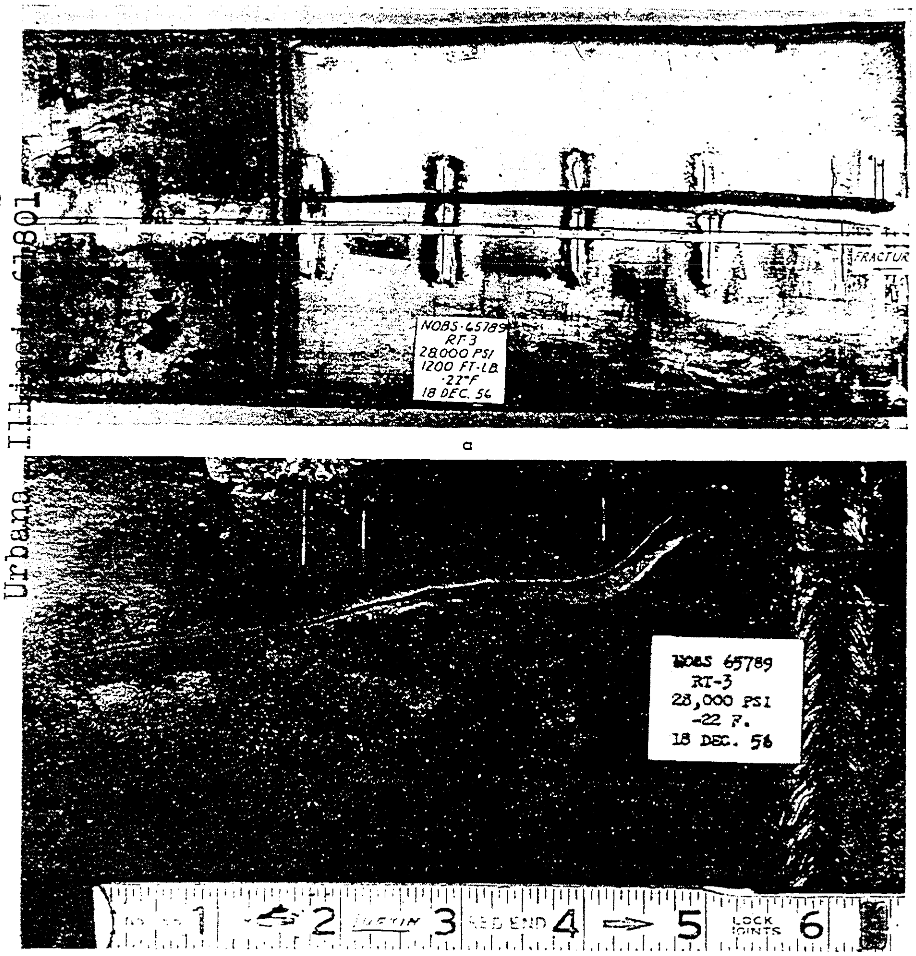

Fig. 12 Arrest of 4-ft long crack by 24-in. wide strake of *T* steel

(a) View of insert showing extent of propagation.
(b) Penetration of arrested crack into *T* steel.

ability; however, propagating brittle cracks are not necessarily attracted to the closest rivet holes and may, in fact, pass between them.

The riveted-arrester specimen without the longitudinal oxygen-cut slot was tested three times with the crack initiated from the edge near the doubler plate. Each attempt to fracture the specimen was made from a different location of the notch as shown in Fig. 8 (*a*). After each test, the fractured portion of the specimen was gouged out and the specimen rewelded for the next test. As can be seen in the figure, the first test was made with the crack initiated from a notch in line with one of the horizontal rows of rivets which connected the doubler and the insert plate. In this test the crack propagated to the rivet hole in the first vertical line. In the second test the crack was initiated from a notch located midway between two horizontal rows of rivets and in this case the crack propagated slightly upward to a rivet hole in the third vertical line. The third test on this specimen was made with the notch located so as to provide what seemed to be the greatest probability for uninterrupted crack propagation; in this test the notch was located just slightly above a horizontal row of rivets. The crack propagated completely across the main plate of the specimen passing approximately midway between two horizontal rows of rivets in the region where the doubler plate was connected. In addition, a crack was initiated and propagated from the far edge of the doubler back to the second vertical line of rivets, as can be seen in Fig. 8 (*b*). This third test indicated that it is possible to propagate a brittle crack across an unslotted riveted arrester. However, it is believed that such a failure would have been less likely if a staggered rivet pattern had been used.

In all of the riveted-arrester tests, the fracture surfaces of the rimmed steel had a brittle appearance and little reduction of area—very similar to the fracture surfaces of the plain plate rimmed-steel specimens being tested in the propagation program.[1] Fractures in both main plate and doubler exhibited this brittle behavior.

Welded-Arrester Specimens

In the welded specimens, 4-, 12-, 24- and 36-in. wide strakes of tough material (steel T) and E12015 electrodes were used in the fabrication of the various specimens to provide an arresting device. These arresting strips were used in combination with 1 to 4 ft widths of starter material (rimmed steel E or Z) in the different test specimens.

In the laboratory tests conducted on various 6-ft wide welded crack-arrester specimens, the following general results have been observed.

(*a*) An E12015 butt weld alone (i.e., not in combination with a strake of T steel) did not stop a brittle crack that had propagated across a 12-in. starter width of rimmed steel.

(*b*) A 4-in. wide strake of T steel stopped the propagation of brittle cracks which had developed lengths of 1 or 2 ft. Shown in Fig. 9 (*a*) is a specimen in which a crack propagated 2 ft and was then arrested by 4 in. of T steel. On the surface there is no indication of crack penetration in or beyond the butt weld, see Fig. 9 (*b*).

(*c*) During a period of about 10 sec, the crack in a specimen with a 3-ft long starter strip propagated completely across a specimen containing two 4-in. wide strakes of T steel which were 4 in. apart. This fractured specimen is shown in Fig. 10 (*a*). In Fig. 10 (*b*) can be seen the inclined fracture surface in both strips of T steel and the typical chevron-marked surface in the rimmed steel. Redistribution of the applied load created slight inelastic buckling at the edge of the specimen.

(*d*) In a specimen with a 3-ft long starter strip and a 12-in. wide strake of T steel, the crack only penetrated approximately 1 in. into the tough steel, see Fig. 11 (*a*). A view of the region in which the crack was arrested is shown in Fig. 11 (*b*). Extreme buckling occurred at the far side of this specimen.

(*e*) The brittle crack in a specimen with a 4-ft starter strip penetrated about 6 in. into and was arrested by a 24-in. wide strake of T steel. This fractured specimen is shown in Fig. 12 (*a*) and a closer view of the region of the T steel in which the crack was arrested is shown in Fig. 12 (*b*). Extreme buckling occurred on the far side in this specimen.

In all of the tests of welded-arrester specimens, the fracture surface of the rimmed and the semikilled steel had a brittle appearance and little reduction of area. However, where a brittle crack was propagated across or into a strake of T steel, the fracture surface in the tough steel was always on a 45-deg plane.

The final load for partly fractured specimens was approximately the same as the initial value for tests in which only a 12-in. long crack was developed. However, the final load, which is eccentric because of the crack, was approximately 90, 60 and 20% of the initial load for 24-, 36- and 48-in. long cracks. Although the loss of load on the specimen does not take place until some time after the brittle crack has propagated to the weld and strake of arrester material, the eccentric loading which follows creates severe bending and extremely high strains in the region at the end of the crack. Bending and redistribution of the applied load may cause buckling at the far edge of the specimen and thus affect further the conditions at the end of the propagated crack. The redistribution of load and the occurrence of buckling at the edge of the specimen undoubtedly have a considerable influence on the behavior of the arrester material. The effect of these conditions on the development and magnitude of strain has not been determined but is under study at this time.

In tests of 6-ft wide plain plates, the entire fracture process occurs in 1 to 2 msec. In most arrester tests, the time for the crack to propagate to the arresting device is less than 1 msec. During this interval, the strain gages across the remaining section (at least 6 in. ahead of the advancing crack) show little response for a period of a few milliseconds and then indicate a redistribution of stress. Shortly thereafter, for the few specimens where the records obtained are sufficiently long and dependable, the buckling at the far side of the specimen, if it occurs, becomes evident. In those specimens where the records were taken for a longer period of time, there was little change in the strain after approximately 100 msec; that is, the strain readings at a time of 100 msec were in good agreement with those measured about 10 sec later.

This program is still in progress. However, an attempt has been made in this paper to describe briefly the work and some of the observations to date. As indicated by the tests which have been described in this paper, strakes of tough steel butt welded to a less ductile material have arrested propagating brittle cracks under certain conditions. It is hoped that further study will help to provide an explanation of the mechanism of brittle fracture arrest, provide a means of evaluating the crack-arresting capability of various materials and eventually make it possible to formulate a dependable basis for the selection of welded crack arresters.

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